Indian J. Phys. **71B** (4), 465–471 (1997)

IJP B
- an international journal

Contribution of cyclotron resonance in enhanced electron precipitation at Brazilian anomaly

U P Singh and D P Singh*

Atmospheric Research Laboratory, Department of Physics, Banaras Hindu University, Varanasi-221 005, India

*Department of Physics, Government College Adampur, Hisar-125 052, India

Received 26 November 1996, accepted 28 April 1997

Abstract : Various *in-situ* as well as at earth surface observations show that the Brazilian anomaly or South Atlantic Magnetic Anomaly (SAMA) is a region where enhanced energetic electron precipitation (EEP) takes place. Contribution of cyclotron resonance in particle precipitation at SAMA region (where EEP is peaked) is computed. It is found that cyclotron mode of whistler wave-energetic electron interaction contributes significantly to EEP at SAMA which is very high at the inner edge of inner radiation belt ($L = 1.1$). In this case, the whistler waves are amplified to have the increased spectral intensity which is consistent with experimental observations of extreme low frequency/very low frequency (ELF/VLF) emissions at $L = 1.1 - 1.5$.

Keywords : Cyclotron resonance, electron precipitation, Brazilian anomaly

PACS Nos. : 94.20.Qq, 94.20.Rr

1. Introduction

The geomagnetic field at earth's surface between 0–100 km altitude, is not symmetric in Northern and Southern hemisphere. The geomagnetic field is asymmetric at or around 60°W–30°E and 100–140°E longitudes. The first region of asymmetry is called Brazilian anomaly or South Atlantic Magnetic Anomaly (SAMA) which has long been recognized as a major sink for radiation belt trapped electrons [1]. Ginzburg *et al* [2] were first to report enhanced electron precipitation in Brazilian anomaly. These observations were made aboard Russian satellite Sputnik-V at an altitude of 300 km in the year of 1960 [also see Ref. 3]. Seward [4] presented the geographical distribution of energetic electron precipitation in this region in 1961 at altitudes between 240 and 410 km during a magnetically quiet period. Vampola and Gorney [5], Nagata *et al* [6] and Imhof *et al* [7] analysed enhanced electron precipitation (EEP) in the SAMA region. The review of the work in this field was presented by Paulikas [8]. Pinto (Jr) and Gonzalez [9] reviewed the work done between 1975–1989 to provide a concise picture of the driving mechanisms that seem to cause the enhanced precipitation of energetic electrons in the SAMA region. In recent years several mechanisms for precipitating energetic electrons have been suggested involving, in general, a type of wave particle interaction.

In this paper, we consider cyclotron mechanism as the dragging mechanism for these electrons and explain why EEP is enhanced in the SAMA region.

2. Method of computation

To see the contribution of cyclotron resonance in dragging trapped electrons to lie in the loss cone, we have to calculate equatorial loss cone pitch angle (α_o) using following equation [10–11]

$$\sin^2 \alpha_o = H_m^3 / L^2\left(4L^2 - 3H_m L\right)^{1/2}, \tag{1}$$

here L is McIlwain parameter and $H_m = (R_o + h_m) / R_o$. R_o is earth radius (6370 km) and h_m is mirror height of bouncing electron.

Following Etcheto *et al* [12], the precipitated flux at a given location is given by

$$J_p(> E) \propto \int_o^{\pi/2} \sin \alpha \, d\alpha \tag{2}$$

and
$$J_p(> E) \propto 1 / \alpha_o, \tag{3}$$

and which can be written as

$$J_p = \text{const.} \times \frac{1}{\alpha_o} \int_o^{\pi/2} \sin \alpha \, d\alpha. \tag{4}$$

Since pitch angles $\alpha \leq \alpha_o$ are already in loss cone, the contribution to precipitated flux will be only by pitch angle $\alpha > \alpha_o$. We can write

$$J_p = \text{const.} \times \frac{1}{\alpha_o} \int_{\alpha_o}^{\pi/2} \sin \alpha \, d\alpha \tag{5}$$

$$= \frac{\text{const.}}{\alpha_o} \times \cos \alpha_o. \tag{6}$$

Since we are interested in calculating contribution of cyclotron resonance in dragging trapped electrons into the loss cone to increase precipitated flux, we have not taken other parameters in eqs. (2)–(6) into consideration. At a given L shell, most of the parameters (characteristic energy *etc.*) ramain unchanged for anomaly or no anomaly region except loss cone pitch angle α_o.

3. Results and discussion

An interesting characteristic of electron precipitation in geomagnetic field is that it is strong function of longitude [13]. This is primarily due to the fact that the mirror altitude (h_m) of a particle varies significantly with longitude, the largest variation taking place in and around SAMA. Figure 1 depicts the variation of geomagnetic induction B for Northern and Southern hemisphere with longitude. Corresponding α_0 values are also shown

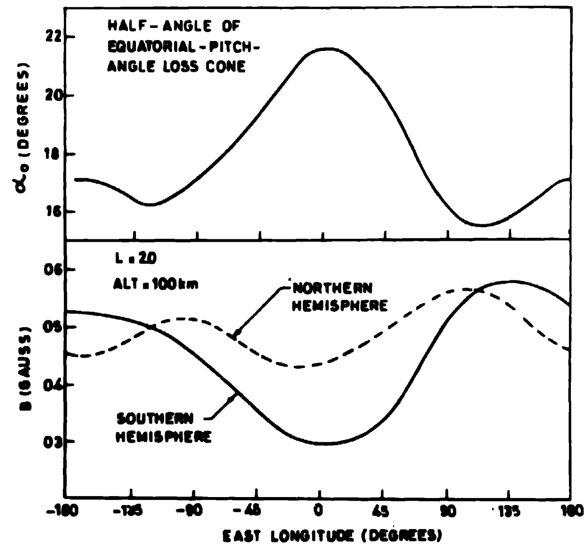

Figure 1. Variation of loss cone pitch angle (α_0) and magnetic induction (B) with longitude at $L = 2$. α_0 corresponds to B(min) in both hemispheres (After C S Roberts [15])

in the upper portion of the figure. When an electron drifts from west to centre of anomaly, its h_m is increased (α_0 is high) and all $\alpha \leq \alpha_0$ will lie in the loss cone to be precipitated. At this position, interacting flux of such electrons is zero due to their precipitation which further starts to build up as electron moves from centre to east of anomaly. In the east of centre of SAMA, B is high, α_0 and h_m are low and no such kind of precipitation as observed in the centre is possible. The precipitation of energetic electrons in their drift from west to centre is now known as wind-shield wiper effect.

The narrowing of cone at east of SAMA shows that EEP cannot be due to wind-shield wiper effect or due to bounce scattering. This is only possible if pitch angle of electron (α) is reduced to α_0 by some other mechanism. Such a perturbation in pitch angles can be caused by electric fields generated during lightning discharges [14], solar wind interactions with magnetosphere, plasma instabilities or plasma not at thermodynamic equilibrium [15]. Vampola and Kuck [16], and Imhof *et al* [17] have interpreted L-dependent peaks of precipitated flux in terms of cyclotron interaction at low latitudes.

Following these workers, we too consider cyclotron resonance mechanism taking place at low L-shells in the SAMA region as a precipitation enhancing process.

We consider two kinds of energetic electrons at the east of anomaly interacting with whistler mode ($f < f_H$, f is wave frequency and f_H is electron gyrofrequency) waves. The first one have mirror altitude $h_m = 0$ km and other have $h_m < 0$ km. The contribution of cyclotron resonance to the EEP in SAMA region is computed applying following expression (see eq. 6).

$$\% \text{ contribution} = \frac{I(\text{SAMA})}{I(\text{NA})} = \left[\frac{[\cos\alpha_o]_{\text{SAMA}}[\alpha_o]_{\text{NA}}}{[\cos\alpha_o]_{\text{NA}}[\alpha_o]_{\text{SAMA}}} - 1\right] \times 100. \quad (7)$$

Here NA means no anomaly region/effect.

Variation of % contribution of cyclotron resonance to EEP with L is depicted in Figure 2. The figure shows that cyclotron resonance contributes significantly to EEP having highest contribution at $L = 1.1$, the inner edge of inner radiation belt and it decreases at $L > 1.1$ The total contribution at $L = 1.1$ for both types of electrons [$h_m = 0$ km $h_m < 0$ km] comes to a high value of 38%.

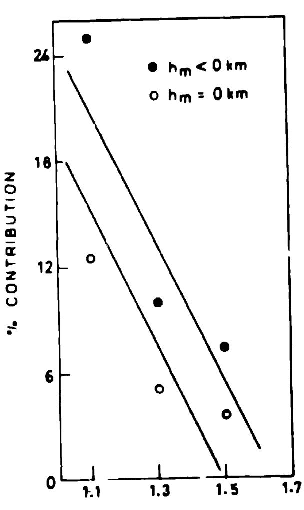

Figure 2. Variation of percentage contribution of cyclotron resonance with L-value

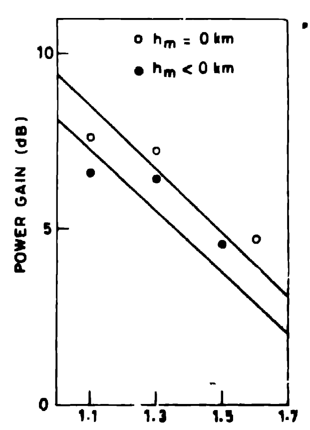

Figure 3. Variation of power gain for 3.2 kHz VLF emissions with L-values

It is well known that during precipitation, electrons lose their energy to amplify the interacting whistler mode wave. The analysis of VLF emissions data observed aboard Ariel 3/4 satellites, show that there exist three zones of intense VLF emissions. The first zone is around 70° geomagnetic latitude, the second around 50° geomagnetic latitude and the third one around or below 30° geomagnetic latitude [18–21]. Hayakawa [22], Singh *et al* [23] and Singh and Singh [24] made a detailed study of Ariel 4 satellite data on low latitude VLF emissions. The analysis of these data reveals that VLF emissions have high intensity (> 60 dB above threshold value of 4.8×10^{-19} Watt. m^{-2} Hz^{-1}, the common observed intensity was 40 dB) and large occurrence rate at 100–140°E longitude. Singh *et al* [23] and Singh and Singh [24] have shown that though these emissions followed a non-ducted mode of propagation [25], the intensification was not due to focusing because of magnetoionic guiding. They were of the view that these VLF emissions have their source in lightning discharges, they were being amplified by cyclotron instability occurring at geomagnetic equator. Following Singh *et al* [23], we compute power gain of 3.2 kHz VLF emissions observed aboard Ariel satellites at $L = 1.1 - 1.5$. The power gain (dB) variation is shown in Figure 3. The curves of Figures 2 and 3 are similar suggesting that cyclotron resonance contributes to EEP in SAMA region causing wave amplification to low latitude whistler mode emissions. It is to be noted here that (i) particle precipitation and wave amplification are co-occurring phenomena [26–28] and (ii) low latitude region is a region where only weak diffusion takes place and this is the strong diffusion which causes wave damping [10–11]. Thus we can write

$$\text{Precipitated flux} \equiv \text{power gain},$$

which is consistent with similar variation of curves in Figures 2 and 3. $h_m < 0$ km electrons produce less power gain. It is because of two reasons :

(1) We have taken anisotropy (A) to be pitch angle dependent [29], such that $A = 0.5 \ln [\operatorname{cosec} \alpha_0]$. In SAMA regions (positions east of centre) where B is maximum, α_0 is minimum having lower anisotropy which further reduces power gain as power gain is directly related with A [23].

(2) $h_m < 0$ electrons lose less energy and then penetrate deep into the ionosphere causing significant ionisation [30]. They can reach upto 70 km in this case, above earth's surface.

Tsurutani *et al* [31] have reported intense low latitude ELF emissions. Similar to our Figure 3, they observed highest intensity at $L = 1.1$ and lowest at 1.7 (see also Ref. [9]). It is to be emphasized here that the position on earth surface where B is highest lies far away from SAMA and this second region of anomaly is called Pacific Anomaly spread between 100–140°E. Thus at these longitudes too, we will get intense ELF/VLF emissions. The low latitude 3.2 kHz emissions recorded aboard Ariel 4, are found to have high occurrence and intense peak in the longitude interval of 100–140°E [22–24].

The centre of SAMA (and its spread) is not a fixed location and may change in subsequent years. Fraser-Smith [32] and Fabino *et al* [33] have shown that in the last two decades (1966–1986), the centre of anomaly has drifted a few degrees. The B (max) and

B (min) also do change. The *B* (max) at $L = 2$ in 1968 was found to be 0.58 Gauss by Roberts [15]. This was only 0.44 at the same location in 1984 as reported by Imhof *et al* [7].

Acknowledgments

One of the authors (UPS) thanks Council of Scientific and Industrial Research, New Delhi for financial support as Research Associateship. DPS is grateful to University Grants Commission, New Delhi for providing financial assistance in the form of a minor research project.

References

[1] A J Dessler *J Geophys Res* **64** 713 (1959)

[2] V L Ginzburg, L V Kurnosova, V I Logachev, A A Rosorerov, I A Sirotkin and M I Fradkin *Planet Space Sci* **9** 845 (1962)

[3] S N Vernov, E V Gorchakov, P I Shavrin and K N Sharvina *Space Sci Rev* **7** 490 (1967)

[4] F D Seward *Livermore Lab Rep* **VCRL/51470** Lawrence (1973)

[5] A L Vampola and D J Gorney *J Geophys Res* **88** 6267 (1983)

[6] K Nagata, H Kohno, H Murakami, A Nakamoto, N Hasebe, T Takenaka, J Kikuchi and T Doke *J Geomag Geoelectr* **37** 329 (1987)

[7] W L Imhof, J B Reagan, E E Gaines and D W Datlowe *J Geophys Res* **89** 10827 (1984)

[8] G A Paulikas *Rev Geophys Space Phys* **13** 709 (1975)

[9] O Pinto (Jr) and W D Gonzalez *J Atmos Terr Phys* **51** 351 (1989)

[10] D P Singh *Indian J Radio Space Phys* **20** 424 (1991)

[11] D P Singh *Indian J Radio Space Phys* **21** 250 (1992)

[12] J Etcheto, R Gendrin, J Solomon and A Roux *J Geophys Res.* **78** 8150 (1973)

[13] J G Roederer, J A Welch and J A Herod *J Geophys Res* **72** 4431 (1967)

[14] U P Singh, A K Singh, D P Singh, R P Singh and R N Singh *Indian J. Radio Space Phys.* **25** 351 (1996)

[15] C S Roberts *Rev. Geophys* **7** 305 (1969)

[16] A L Vampola and G A Kuck *J Geophys. Res* **83** 2543 (1978)

[17] W L Imhof, E E Gaines and J B Reagan *J. Geophys. Res* **86** 1591 (1981)

[18] K Bullough, M Denby, W Gibbons, A R W Hughes, T R Kaiser and A R L Tatnall *Proc. Roy Soc* (London) **A343** 207 (1975)

[19] K Bullough, A R W Hughes and T R Kaiser *Proc Roy. Soc.* (London) **A311** 563 (1969)

[20] K Bullough, A R W Hughes and T R Kaiser *Spacecraft Studies on VLF Emissions* (*Magnetospheric Physics*, ed B M McCormac) (Holland : D. Reidel) p 231 (1974)

[21] T R Kaiser and K Bullough *Ann. Geophys.* **31** 137 (1975)

[22] M Hayakawa *J Geomag. Geoelectr* **41** 573 (1989)

[23] D P Singh, U P Singh and R P Singh *Planet. Space Sci* **40** 1425 (1992)

[24] U P Singh and D P Singh *J Geophys. Res* (Communicated) (1997)

[25] R A Helliwell *Whistler and Related Ionospheric Phenomena* (Stanford, California, USA . Stanford University Press) (1965)

[26] N Cornilleau-Wehrlin, R Gendrin and M Tixier *Space Sci. Rev* **22** 419 (1978)

[27] J Solomon, N Cornilleau-Wehrlin, A Korth and G Kremser *J. Geophys. Res* **93** 1839 (1988)

[28] N Cornilleau-Wehrlin, J Solomon, A Korth and G Kremser *J. Geophys. Res* **90** 4141 (1985)

[29] C F Kennel and H E Petschek *J Geophys. Res.* **71** 1 (1966)

[30] R A Helliwell, J P Katsufrakis and M L Trimpi *J. Geophys Res* **78** 4679 (1973)

[31] B T Tsurutani, E J Smith and R M Thorne *J. Geophys Res* **80** 600 (1975)

[32] A C Fraser-Smith *Rev Geophys.* **25** 1 (1987)

[33] E B Fabino, N W Peddie, D R Barraclough and A K Zunde *IAGA Bulletin* **47** (1983)